

LCRO: The Lunar Cosmic-Ray Observatory

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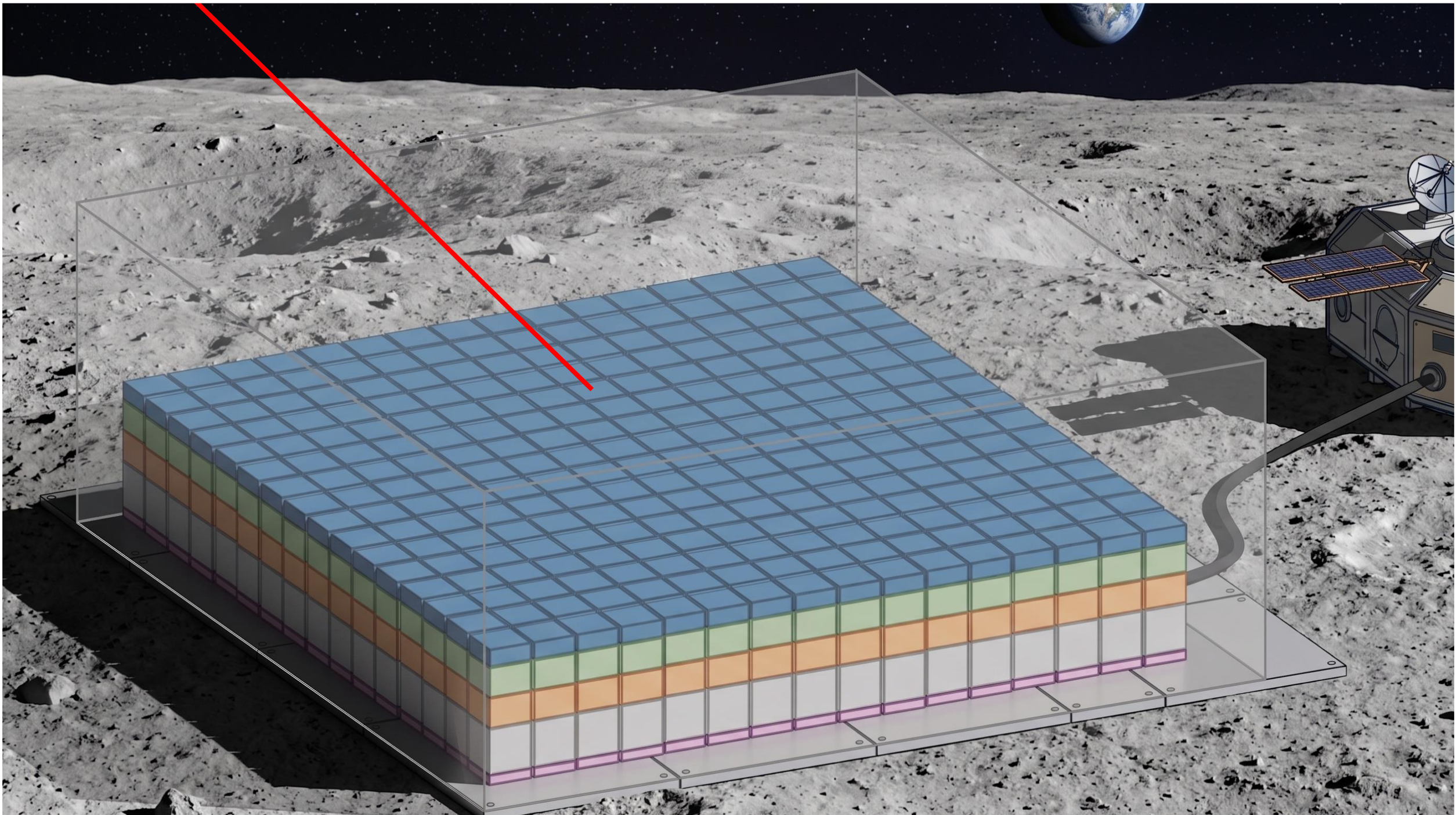
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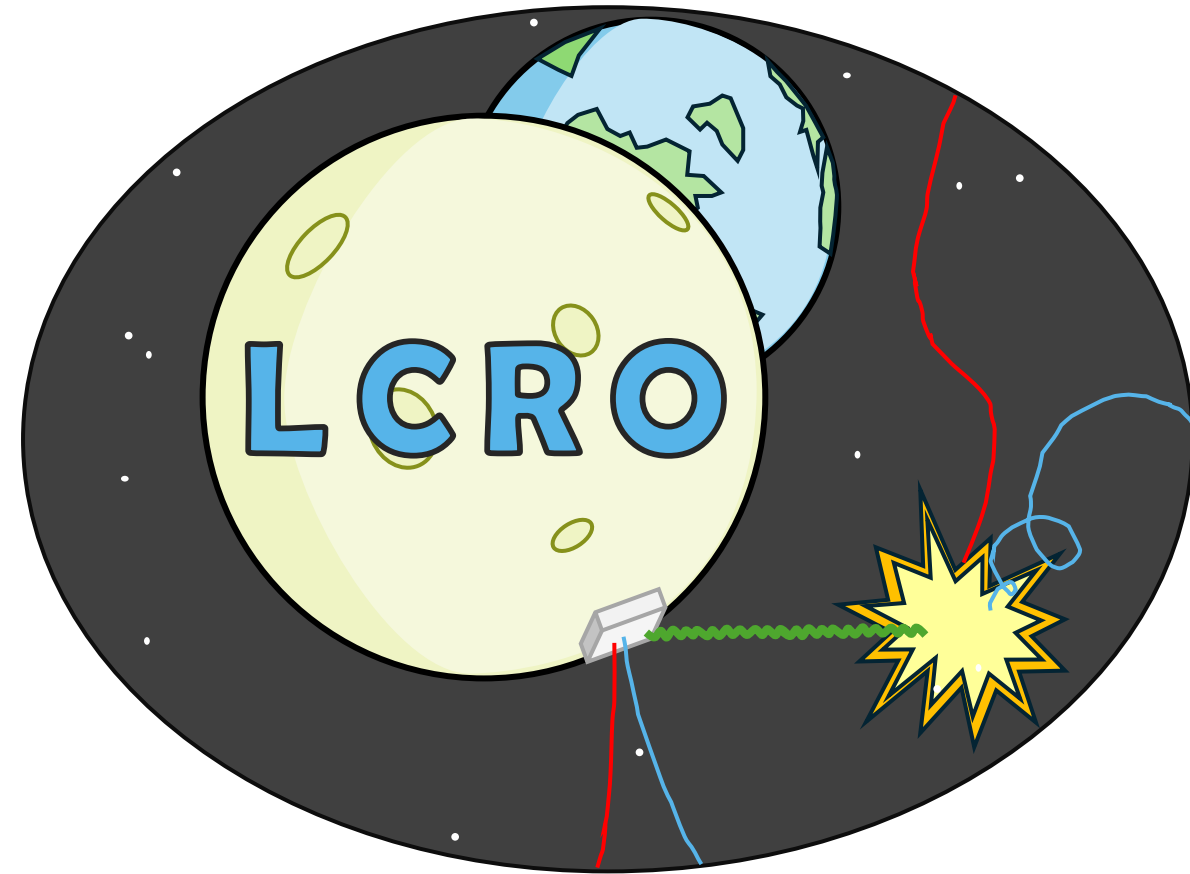
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One Observatory, Multiple Messengers



The large, calorimetric design of LCRO enables observations of:

Cosmic-ray nuclei

- Energy spectra encode how particles were accelerated to high energies and transported through the galaxy

Cosmic-ray electrons

- Nearby sources and dark matter annihilation can produce clear spectral features at GeV-TeV energies

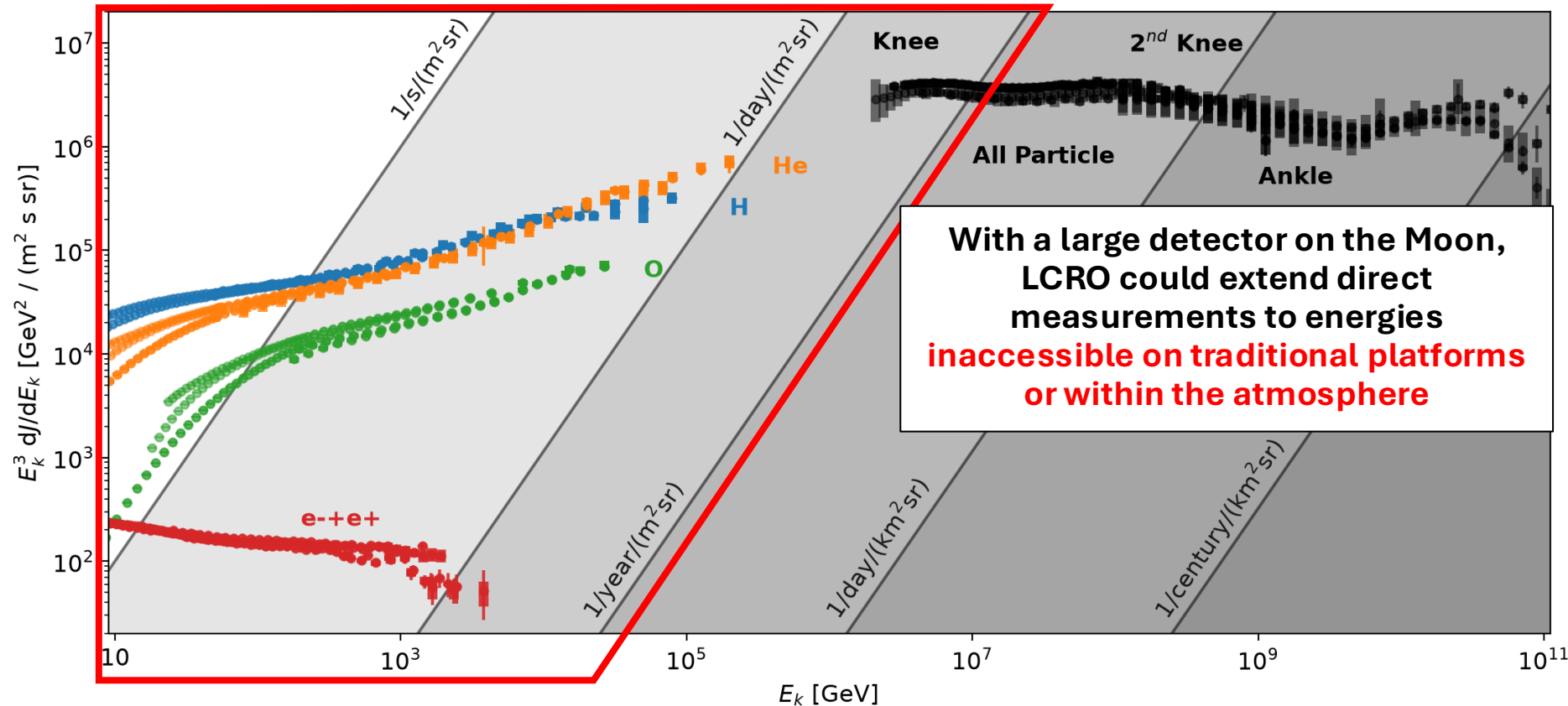
Gamma rays

- Evidence of acceleration and high-energy populations can be inferred from astrophysical source populations

Galactic Cosmic Rays to the Knee

Cosmic rays are energetic charged particles that flow through the galaxy, carrying information in their...

- Energy spectra:
How are CRs accelerated and what processes govern how they propagate?
- Abundances:
What elements are in the material reservoir at the source and how effectively are species accelerated?
- Incident direction:
Are there nearby sources or propagation effects creating anisotropy in the flux?



Direct measurements at sub-PeV energies are **species-resolved**, and have revealed a number of unexpected spectral features

Indirect measurements at ultra-high energies **utilize the atmosphere** as a massive detector medium, but are unable to determine the incident particle species

Science Traceability Matrix

Science Goal	Measurement	Mission Requirements	LCRO Projected (16x16 Towers)			
Clarify the nature of galactic particle accelerators	Species-resolved GCR fluxes to the Knee region (1-10 PeV)	• Charge Range • Charge Resolution • Energy Range • Energy Resolution • Large Exposure	Acceptance/ Geometrical Factor	G.F. only	18 m ² sr	
Constrain the parameters governing propagation of GCRs through the galaxy	Secondary to primary ratios from GeV to PeV energies			Electron	15 m ² sr	
				p/nuclei	15 m ² sr	
			Effective Area		8 m ²	
Confirm or reject the significant impact of a local source of electrons	Cosmic-ray electron flux from GeV energies through 20+ TeV	• Hadron Rejection • Energy Resolution • Exposure	Field-of-View		75°	
			Angular Resolution		0.05° (1 TeV)	
			Energy Resolution	EM	1 – 2%	
				p/nuclei	30 – 35%	
Localize sources of multi-messenger transient events for follow-up	Direction-sensitive, low-latency gamma-ray observations	• Angular Resolution • Effective Area • Field of View	Charge Range		0 – 28+	
			Charge Resolution	p/ ₂ He	0.1 e.c.u.	
Search for acceleration signatures from sources of astrophysical neutrinos	Observations of the GeV sky over long periods of time	• Angular Resolution • Exposure • Energy Resolution • Hadron Rejection		₆ C ₇ N ₈ O	0.2 e.c.u	
				₂₆ Fe	0.3 e.c.u	
				e/p Separation		1:10 ⁵

A Modular Approach

Why haven't we made these measurements already?

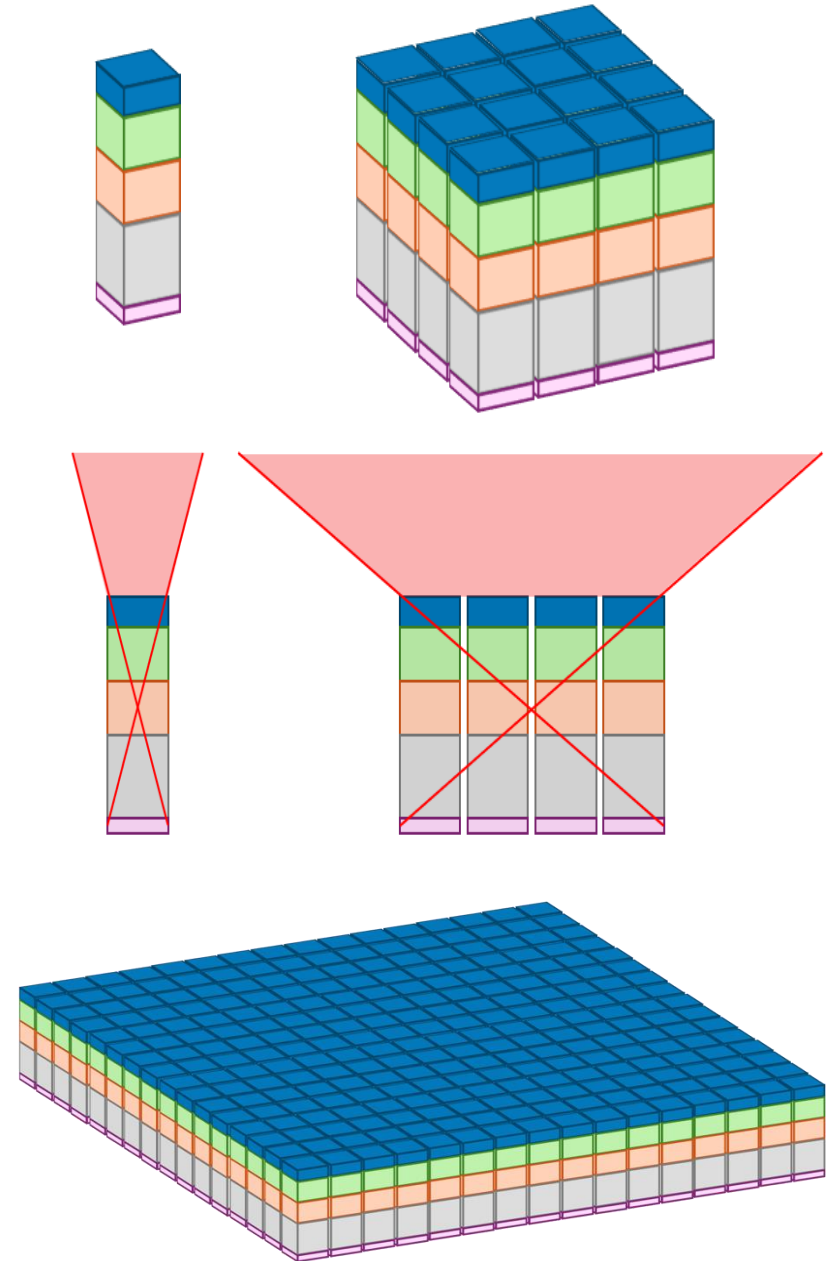
➤ Mainly, the required **active detector size**

LCRO avoids the lift requirements of an individual launch vehicle using a modular tower design

- Lower per-unit launch mass
- Distributed installation not critically tied to the schedule of any individual launch opportunity

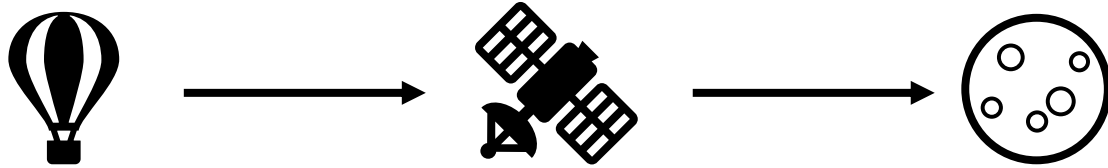
Gradual deployment of an unprecedentedly large array, with science return scaling along the way

- **Single tower:** validates concept and performance
- **Small array (4 – 25 towers):** improved aspect ratio quickly increases geometrical factor for science observations and distributed operations validated
- **Observatory-scale array (100 – 256 towers):** data collection to achieve primary science goals



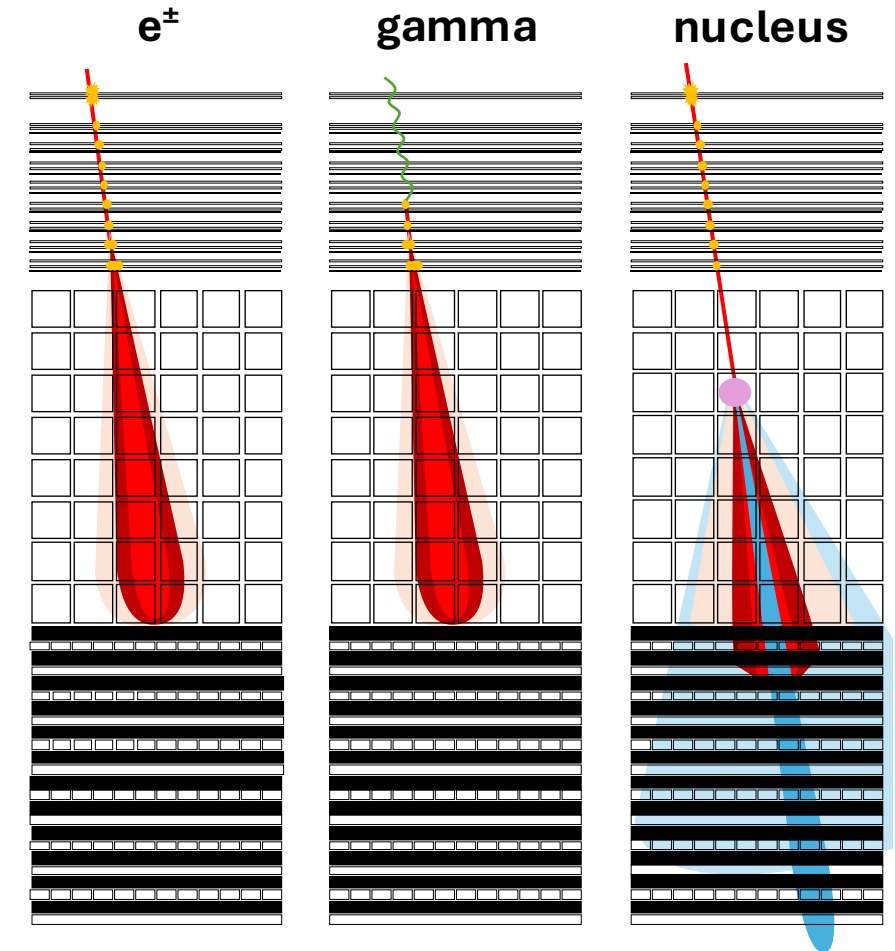
LCRO Towers – A Closer Look

LCRO draws conceptual heritage from a number of successful balloon and space missions, including CALET, CREAM, and Fermi-LAT.



Each tower contains:

- LGAD-based charge detector with time-of-flight capabilities for backscatter rejection
- Silicon-strip based particle tracker detector with tungsten foils to stimulate interaction
- Deep calorimeter of inorganic scintillators to effectively absorb electromagnetic showers
- Sampling calorimeter with thick absorbers to measure tail of showers from nuclear interactions
- Neutron detector to characterize neutron albedo and content in hadronic tail



Electron and photon primaries produce pure EM showers, which are mostly absorbed in the upper calorimeter. Protons and nuclei undergo inelastic interactions in the instrument, producing penetrating charged secondaries that are measured in the sampling calorimeter.

Programmatic Synergy & Enabling Technologies

Science Alignment

LCRO science targets address multiple **Astro2020 Decadal Survey** and **NASA Enduring Quests – Daring Visions** roadmap questions, such as:

- How does the Universe work?
- What are the properties of dark matter?
- How do gas, metals, and dust flow into, through, and out of galaxies?
- Are neutron star mergers the main site of r-process nucleosynthesis?

Moon Base Infrastructure

LCRO is enabled by the implementation of a long-term base on the lunar surface and the required infrastructure, including:

- Astronaut/robotic support for installation of towers and the micro-meteoroid protection “shed”
- Communications and telemetry resources
- Power generation resources
- On-location compute resources?

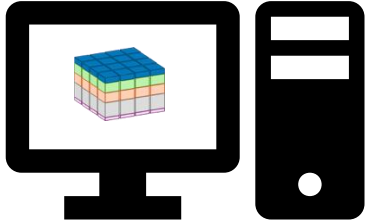
Frequent Launch Cadence

NASA is targeting several lunar-bound launches per year under the CLPS program, enabling the gradual installation of the LCRO design

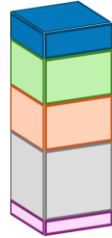
In-Situ Resource Utilization

Absorbers for sampling calorimeter could be fabricated with processed lunar regolith, further reducing the required launch mass per tower

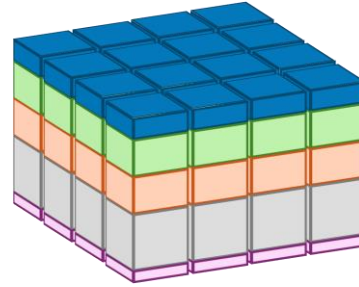
The Path to Readiness



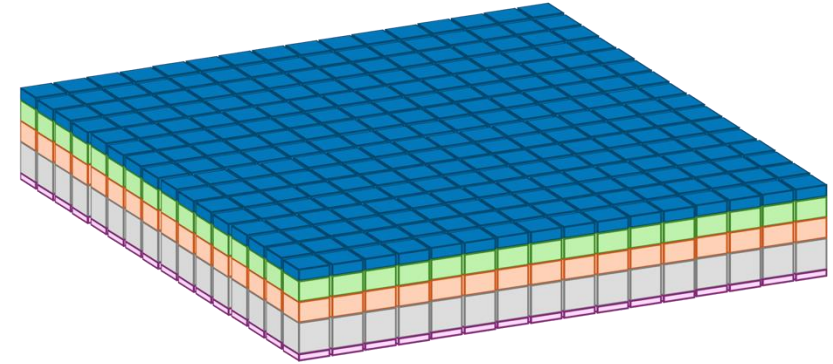
Now: simulations,
design optimization,
LGAD development



~2030: pathfinder
tower readiness for
CLPS deployment



~2030s: gradual
expansion of array on
subsequent launches



~2040s: large area array (>10 m²sr)
performing long-term operations to
achieve primary science goals

Outstanding Milestones

- Mature thermal considerations – minimize need for survival batteries
- Data throughput/onboard processing – event prioritization, remote analysis
- Flexible trigger – enable readout of multi-tower events without locking array
- Radiation backgrounds on Moon – impact of albedo flux on operations
- Anti-coincidence optimization for gamma-ray observations

Summary

LCRO is a scalable concept for a modular astroparticle telescope on the Moon

- Probes particle acceleration from astrophysical sites
- Sensitive to EM signatures of dark matter annihilation
- Monitors Solar radiation impacts at a long-term Moon base
- Searches for TDAMM counterpart events

LCRO synergizes with NASA agency priorities

- Supports lunar surface exploration and development
- Compatible with CLPS frequent delivery goals
- Relies on infrastructure of a long-term lunar presence
- Furthers cooperation with key US international partners

LCRO measurements are unique and pioneering

- Detector effective geometry more than 10x larger than current-generation space missions
- Species-resolved measurements not possible from large ground-based observatories

